CHAPTER 7
MONITORING PERFORMANCE

7-1. General.

a. Although periodic visual inspections are an essential part of performance monitoring, destructive trends may be present for several years before visual signs of foundation distress appear. Gradual warming of frozen soil has little effect on performance until the melting point is reached. Severe damage can then rapidly develop if the foundation has high ice content. Exceptional weather conditions or changes in operation may also induce more abrupt deviations. By installing instrumentation, such efforts can be detected and stopped before damage results. If distress does occur, instrumentation provides the evidence needed to establish the source of the problem which otherwise must be defined by deductive reasoning, a process of limited value where unique foundation conditions are encountered.

b. Where possible, basic instrumentation for monitoring the performance of a foundation and structure should be installed prior to construction in conjunction with the program of subsurface exploration. Frost-free benchmarks, temperature sensors, frost gauges, water wells and other devices installed in drill holes at that time will define the undisturbed conditions as well as any subsequent changes caused by the facility. Additional instrumentation should be installed during the construction. The type and amount of instrumentation and the observational frequency depend on the type of building and foundation, its purpose, and the subsurface and environmental conditions.

c. In 1943 Dr. Karl Terzaghi[196] wrote: "Records with potentially valuable information have become worthless on account of a few omissions which escaped attention at the time the record was filed. Others have never served a useful purpose because the data were so poorly presented and cumbersome that no one could afford the time to unravel and digest them." Consequently, well organized systems for data collection and analysis should be established at the time instrumentation is installed and summary data reports prepared periodically. Photographs taken before, during, and after construction are often useful. Broad comparisons and evaluations on a regional or extra-agency basis also provide extremely valuable input for development of new and improved criteria. Copies of such data and reports should be submitted to CRREL for incorporation into its records under its mission of obtaining performance feedback, maintaining cognizance and disseminating information on cold regions science and engineering.

7-2. Inspections. Periodic inspection of the performance of facilities is essential to detect possible evidences of foundation distress. Written and photographic records of inspections should be maintained so that the development of problems can be fixed in time. Additional instrumentation should be installed when needed to assist inspection. A brittle plaster patch (tell-tale) placed over a crack will indicate if movements are continuing. Mechanical and electrical strain gages may also be considered. Inspection of interconnecting utilities and adjacent areas is also important because leaks in utility lines, insufficient surface drainage provisions, disruption of natural ground water, thermal disturbance and other factors may cause unanticipated problems.

7-3. Vertical movement measurement.

a. Measurement points should be installed at the key points on the foundation so that frost heave or settlement deflections can be monitored. The points should be established during construction and their elevations referenced to a frost-free stable benchmark (Chap 5) located some distance away in an undisturbed area. If an adequate benchmark is unavailable, the relative elevations of points on the structure should at least be measured. Since it is not always possible to predict potential problem areas, the elevation of numerous points on and around the foundation should be established initially. Subsequent surveys need not be as comprehensive. If foundation movements do occur, the pattern of measurement points can then be adjusted as needed. Allowance should be made for removal, blockage and damage to points during the life of the structure by establishing enough points so as not to be too dependent on any one.

b. Although expensive, manometer systems are occasionally used to measure the relative elevation of points on a structure[130]. By interconnecting the upper ends of the manometers with a hose, variations in atmospheric pressure from one point to the next can be eliminated. To avoid introducing errors caused by variations of liquid density with temperature, the manometers should be maintained at the same temperature, or temperatures should be measured and corrections applied.

c. Under some conditions, such as where soil creep is occurring, measurement of horizontal components of movement may also be needed.

7-4. Temperature sensing. Where remote sensing of temperature is necessary electrical systems are generally required. These are the most versatile and most frequently used systems for monitoring freeze and thaw conditions in the ground. Either thermocouples or thermistors may be used. The choice is based chiefly on the degree of precision required. Sohlberg[92] presents a comprehensive analysis of the basic systems and their sub-features. Thermohms, which are wound wire resistors that experience resistance change with temperature, have been used extensively in the past but are now little used because of their expense and because their substantial size, their volumetric heat capacity, and their heat conductance capacity in both probe and cable present substantial potentials for error in temperature measurements.

a. Thermocouples.

(1) In essence, a thermocouple is a very weak battery created simply by joining wires of two dissimilar metals. The strength of this "battery" changes with changing temperature and by measuring the small voltage produced the temperature at the bimetallic junction can be determined. When an electrical circuit consisting of two dissimilar wires is closed at both ends, two thermocouples are created. They are in electrically opposite directions and if the two junctions are at the same temperature, the voltage produced by one offsets that produced by the other. If the two junctions are not at the same temperature, a net voltage difference is produced. Consequently, it is not the temperature at a single thermoelectric junction that is measured but rather the difference in temperature between two junctions. Thermocouple circuits are generally arranged so that one of the junctions (the sensor) is placed at the point where an unknown temperature is to be measured and the other (the reference) is placed in a mixture of ice and water which maintains itself at 0 °C (32 °F). The difference in emf is usually measured by millivolt potentiometer together with an unsaturated mercurycadmium standard cell voltage reference. An electronic null detector should be used with the potentiometer. The two dissimilar wires commonly used are copper and constantan. Tables are available[2] for converting voltage readings obtained on a precision potentiometer for these wires when the reference junction is maintained at 0°C (32 °F). If field measurements on a top quality installation are obtained carefully, with first rate equipment, the temperatures can be obtained within about 0.4 C (3/4 F) (+) of the true values. If the measurements on a given thermocouple assembly are all made in a single operation over a reasonably short period of time, so that temperatures do not change significantly, the relative temperatures indicated between the thermocouples can be correct within much closer limits. Often differences in temperature between various points are much more important and useful than actual temperature levels. Since the nucleation temperature is usually displaced below 32 °F in finegrained soils, the positions of interfaces between frozen and unfrozen materials are usually more accurately determined by changes in slope of the curve of ground temperatures vs. depth than by the positions of the 3-°F isotherm. To take maximum advantage of this situation, differential values of emf between sensor thermocouples may be measured directly. Since experience indicates that the accuracy level of portable potentiometer field work is about + 0.1 to 0.2 F (± 0.1 °C), differential temperature measurements may approach this degree of accuracy on an individual assembly if all other sources of error, including thermocouple wire characteristics, influence the apparent emf's from all thermocouples equally. To enhance the probability of the latter situation, it is desirable that all the thermocouples in a given assembly be made from the same run of thermocouple wire. Thus, in actual frozen ground measurements, thermocouples may often be used to greater advantage than their capacity to yield true temperatures would suggest, so long as temperature gradients are reasonably pronounced.

(2) Thermocouples are relatively simple and cheap compared to other electrical ground temperature measurement systems. They give good results when temperature gradients are large enough so that very high precision in individual readings is not needed. Their disadvantages include the problems of making and maintaining ice baths and of using and protecting standard cells under winter conditions. In order to obtain reliable temperature measurements, any potentiometer should be maintained at a temperature above 0 °F and the ice bath container kept above 3' °'F. This is best accomplished in the field in winter by placing the potentiometer in a shock-mounted heated (electric or exhaust gas) enclosure in an oversnow or other vehicle and making provision for the observer to carry the ice bath container and the potentiometer batteries and standard cell beneath his parka connected to the potentiometer by extension leads. The leads from the thermocouple cable can then be fitted with a suitable connector and attached directly to a mating connector on the potentiometer enclosure. The thermal gradient across the signal load connector will cause a zero offset but the amount of this offset can be easily determined by connecting the input terminals on the potentiometer together with a short length of wire and reading the offset voltage.

b. Thermistors. When greater precision is needed than is obtainable with thermocouples, thermistors of a select type, stabilized and properly calibrated, should be used.

(1) Thermistors are semiconductors consisting of compounds of various metal oxides which exhibit extremely large changes in resistance with temperature change. Resistance variation with temperature is approximately exponential and a fairly elaborate calibration procedure is required. Sohlberg[92] has described such a procedure. A Wheatstone bridge is used to

measure the thermistor resistances and the calibration curve used to convert to temperature. Thermistor systems are complex to fabricate and cost more than thermocouples but careful field fabrication, installation and observation techniques can produce results repeatable to better than 0.01 °C (0.02 °F) and accurate to better than 0.05 C (0.09 F). Where slight temperature changes are critical their extra expense may be justified. However, in foundation work the added precision often may not be usable to real advantage. Experience has shown that uncalibrated thermistors with direct reading instruments are seldom accurate to 1 IF. An assembly intended for underground installation must be very carefully protected against moisture, because variations of moisture content within the system would change resistances in both the bead and the insulation and hence the apparent temperatures, Thermistors of the type contained within a shock resistant glass bead protective cover should be used and the connecting system of wires and insulations should be assembled with elaborate precautions against moisture penetration. Because thermistors are also pressure sensitive, the thermistor beads must be surrounded by protective metal sleeves or other enclosures within the assembly when pressures such as from freezing of soil or water may occur. Possible errors caused by resistances of leads and contacts in the circuits must be avoided. The thermistors must be stabilized by an accelerated aging process at temperatures well above the operating range and thermal stress adjusted by cycling to temperatures below those expected in application.

(2) Thermistors eliminate the ice bath problems of thermocouples and the problem of thermal gradients across the signal lead connector, making field observational techniques less complex. However, a heated shock-mounted enclosure is still required to house the Wheatstone bridge, in the same manner as for the potentiometer for thermocouples, for reliable field results. Care must be taken to control the amount of current put through the thermistor during the Wheatstone bridge measurements so as not to change its resistance by more than the accuracy of measurement required. In precise work, errors due to thermocouples in the system must be avoided by proper observational techniques.

7-5. Other systems for freeze and thaw monitoring. Several systems other than thermocouples or thermistors are possible for locating the interface between frozen and unfrozen materials and may under some conditions be used in their place. Some of these do not require the assumption of a freezing temperature but determine the interface directly.

a. Probing. In summer, a steel rod can be driven through unfrozen soil in the annual thaw zone until it encounters underlying permafrost. Several methods of driving may be used. In soft, fine-grained soils a sharpened ¼ to ½-in.-diameter steel rod can be pushed down to as much as 15 feet[55] with the help of a pair of clamp-grip pliers as illustrated in figure 7-1a. By making a hole part way by some method, hand probing can be extended further. In slightly stiffer soils a sledgehammer may be needed. Hand augering or test pitting may also be used. For soils in which manual methods of penetration are difficult or impossible, or when a frozen layer must be penetrated, a drill rod or other rod can be driven by a pneumatic drill. Regular exploration, auger or other power-operated drill rigs may also be used. The interface between a frozen layer and an underlying unfrozen layer will usually be detectable by the decrease in resistance to penetration. However, if there is question, the scheme shown in figure 7-lb may be tried, raising the L-shaped rod in contact with the wall of the bore hole until the interface is felt.

b. Soil electrical resistance. When a soil freezes, a large increase in its electrical resistance occurs. This resistance can be measured between copper or conductive epoxy electrodes on the outside surface of a nonconductive pipe which is buried vertically in the soil. The variation of soil resistance with depth determined with this device delineates frozen and unfrozen strata. A schematic of a device developed by Aitken at CRREL'6 together with typical electrical resistance data are shown in figure 7-2. The CRREL tests were accomplished successfully using a low level direct current system. In some soil conditions it might be necessary to make an a-c resistance measurement to avoid polarization at the electrodes.

c. Seismic. The rigidity and consequently the seismic velocity of soil increases when it is frozen. Consequently, conventional refraction seismic surveys can be used to determine the depth to frozen ground below unfrozen material in the same fashion that bedrock is delineated. For relatively shallow annual thaw zone depths, special seismic equipment capable of handling extremely short refraction time intervals must be used. However, the thickness of a frozen layer (annual frost or permafrost) cannot be determined by refraction seismic methods. Reflection type equipment is currently being tested for use in permafrost areas[84,85,124].

d. Color change of material within a tube inserted into the ground. If a sealed tube filled with moist sand is inserted into the ground inside of a fixed outer tube, sealed at the bottom, positions of frozen and unfrozen zones in the ground can be determined at any desired time by withdrawal and inspection of the tube. Dyes such as methyl blue or fluorescein are used to intensify the color difference. Devices of this type have been investigated or used in Alaska by the Permafrost Division

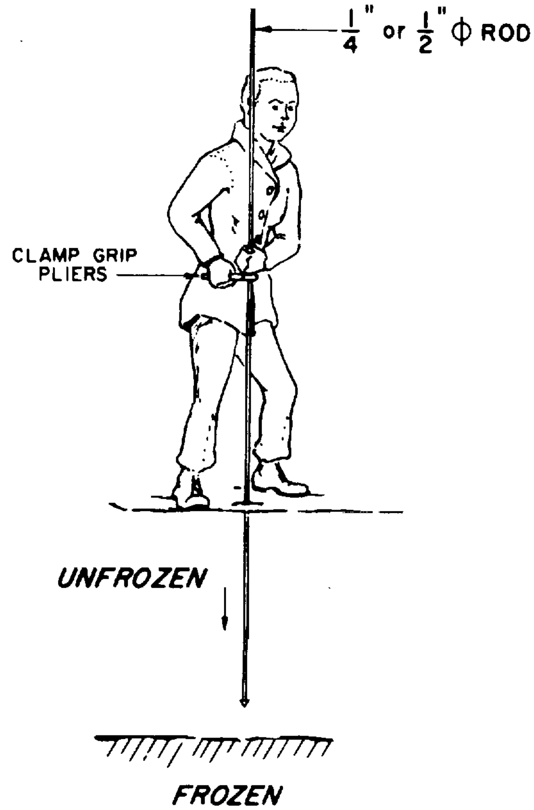

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Figure 7-1a. Permafrost and frost probing techniques (by CRREL).

(Probing to frozen ground.) of the Corps of Engineers (in the early 1950's), in Greenland by the Arctic Construction and Frost Effects Laboratory (in the mid-1950's), in a number of North American locations by CRREL (in the late 60's)[44], in Scandinavia as reported by Gandahl[16], and in Canada by the Saskatchewan Dept. of Highways[116] and the Division of Building Research, National Research Council of Canada. Advantages are simplicity, economy, and avoidance of electrical complexities. Potential disadvantages are (a) lack of thermal correspondence of the sand in the tube with the surrounding soil, with resultant errors, (b) expansion of the inner tube and inability to withdraw it under certain freezing conditions, and (c) lack of detailed thermal gradient data.

7-6. Monitoring groundwater.

a. Simple observation wells have generally proven to be the most reliable method of monitoring groundwater elevations. To prevent cutoff of water by frozen zones the entire length of the casing should be perforated. Since frost action can progressively lift the casing, heave prevention measures should be employed (chap 5).

b. In the fall the elevation of groundwater begins to decrease as soon as the ground begins to freeze (fig. 2-4)[35]. Water standing in an observation well freezes at the top when the frost line reaches it. Because the ice is frozen to the pipe it does not drop with subsequent lowering of the water table. It has been observed that after ice in such wells is cut through at a later date, the water in the well drops below the level of freezing as suction is released and thereafter remains unfrozen (provided the well is covered) unless the frost line reaches the new depth. Consequently, adequate time should be provided for equilibrium to develop once the ice is cut and the suction released, before readings are accepted as valid.

c. A water level indicator device utilizing an electrical contact and visual or audible signal is recommended for measuring the water table position in the well and may be obtained from soils testing equipment suppliers. For very shallow depths a tape or ruler may suffice. To prevent freezing, kerosene has been added in wells to displace a portion of the water column. Air pressure has also been used with limited success in sealed wells to force the water below the frost line. Since the pressure is released when a reading is taken, this method is useful only in highly permeable soils where stability is rapidly achieved. After the measurement is made, the well is again pressurized[65]. Williams and vanEvardingar[209] have reviewed the state-of-the-art of groundwater measurement in permafrost regions, including use of soil moisture cells. However, under the severe condition, encountered on construction projects, moisture cells may not always perform reliably[37].

d. In areas of seasonal frost, electrical resistance gages and various types of pore pressure measuring equipment (piezometers) can also be employed, provided that the sensing element is located below the maximum depth of frost penetration. Freezing of water in the tubing of standpipe type piezometers can be a problem. Carlson, Kane and Bowers[129] and Slaughter and Kane[192] have reported on use of piezometers in recent groundwater studies in central Alaska. Dye solutions can be used to trace the paths and quantity of groundwater flows. This technique was successfully used to study ground flow in the annual thaw zone at Thule AB[105].

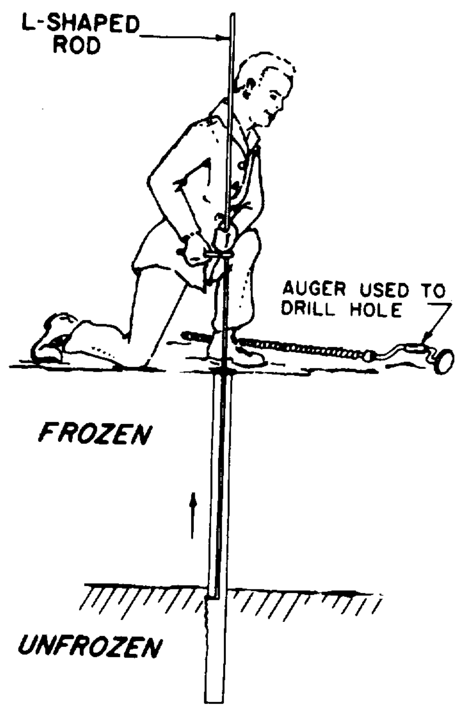

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Figure 7-1b. Permafrost and frost probing techniques. (Probing through frozen ground.)

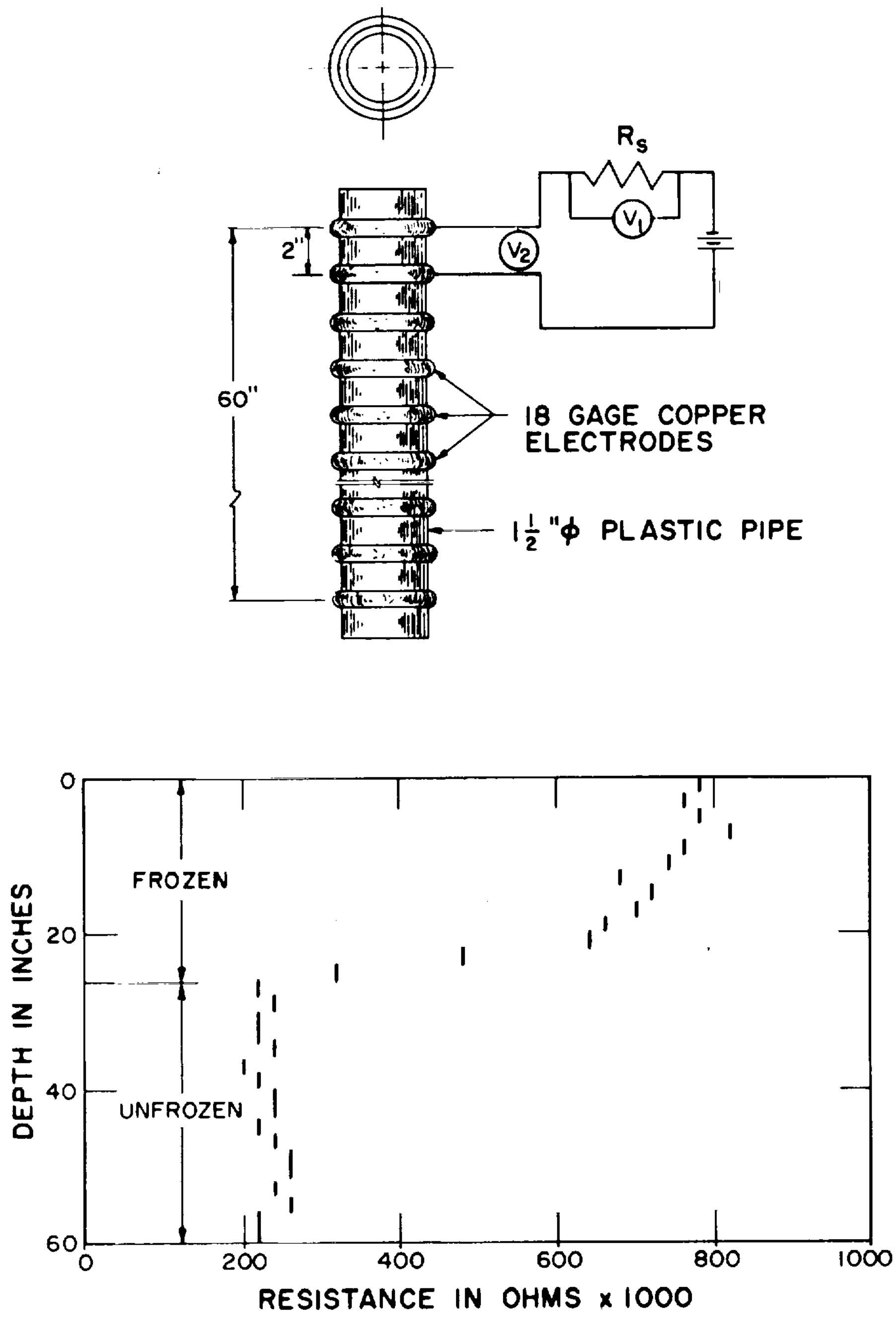

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Figure 7-2. Electrical resistance gage for determination of frost penetration (by CRREL).